

Master's Thesis

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# Market Integration and Commodity Prices: The Case of Prussia

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Department of Economics  
Ludwig-Maximilians-Universität München

**Vahid Ahmadi**

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## Abstract

Diving into the intricate tapestry of 19th-century Prussia, the study examines the multifaceted impact of railway development on the economy, industrialization, and demographics. By scrutinizing the nexus between railway expansion and crucial economic indicators such as trade, inland locomotion, and labor mobility, the research uncovers the transformative influence of improved connectivity. The core focus of the study centers on assessing the profound effects of industrialization and railway advancement on market integration through the lens of commodity prices. Employing innovative methodologies, including the Callaway and Sant'Anna difference-in-differences approach and panel data fixed effect estimation, the research disentangles the complex interplay between railway networks, market integration, and other contributing factors within the Prussian context. Drawing upon historical and economic data sources, the investigation reveals how railway development shaped the coherence of Prussian markets in the 19th century, with a particular emphasis on the novel application of Dijkstra's shortest path algorithm to enhance the precision of distance measurements. The findings illuminate the dynamic interrelationships among railway infrastructure, market dynamics, and societal progress, offering valuable insights into the role of technological advancements in shaping historical economic trajectories.

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# 1 Introduction

In the intricate tapestry of economic history, a compelling narrative emerges from the interwoven relationship between market integration and the convergence of commodity prices. This study embarks on a journey through 19th-century Prussia, focusing on the convergence of commodity prices across its diverse cities as a lens to unveil the story of its market integration. Central to this narrative is the transformative force of railroad development. As iron tracks crisscrossed the Prussian landscape, they not only redefined its physical geography but also ushered in an era of unprecedented connectivity. This paper delves into the symbiotic relationship between the growth of railroads and the integration of Prussia's markets, shedding light on how these historical rails facilitated not only the movement of goods but also the harmonization of economic interests.

Throughout the 19th century, Prussia underwent a profound economic evolution, guided by strategic shifts in agriculture and the rise of industrialization. Starting in the 1830s and 1840s, the economic landscape began to transform as agricultural practices were restructured. Innovations like sugar beets, turnips, and potatoes revolutionized food production, creating a surplus in the rural population that could be channeled into nascent industrial centers. This transition from agricultural life to urban industry laid the groundwork for a changing economic paradigm, as the industrial sector gained momentum.

In the early stages of Prussia's economic transformation, the textile industry played a central role as industrialization began to take root. However, a significant turning point occurred in 1834 with the establishment of the Zollverein, an economic coalition that dismantled trade barriers among member states. This coalition acted as a catalyst for integrating local markets, leading to economic expansion within Prussia's borders. The 1840s marked a pivotal period when growing demand for professionals like middle managers, engineers, and skilled machinists fueled economic growth. Investments in crucial sectors such as coal and iron followed suit, reshaping Prussia's economy and propelling it into an era of industrial progress. Concurrently, in the early 19th century, the introduction of railways in Germany elicited diverse perspectives. Visionaries such as Friedrich Harkort and Friedrich List recognized railways' potential to stimulate the economy and unify fragmented states, initiating railway construction in the 1820s and 1830s. However, concerns about environmental impacts and disruption to existing livelihoods also emerged, highlighting the multifaceted implications of this technological advancement.

The profound impact of railways on economic growth during the Industrial Revolution is widely accepted. These transformative networks connected regions, streamlined goods movement, and ignited industrial and commercial activity. Prussia's recognition of railways' potential led to nationalization in 1880 with dual intentions: lowering freight rates and ensuring equitable pricing. However, the initiative diverged as railways became a major state income source due to government profit management. This decision, impactful yet consequential, influenced Prussia's economic trajectory. Railroads' transformative role in the 19th-century's Industrial Revolution, often seen as its linchpin, has been extensively debated. Scholars like Fishlow (1965), Fogel (1962), Rostow (1962) dissected their influence, quantifying their impact via social savings. This concept facilitated comparative evaluations of railroad-induced contributions to growth across early-adopting countries. Assessments, elaborated by O'Brien (1983), revealed varied outcomes—4% to

25% of Gross National Product—dependent on nations and historical contexts.

Delving into the intricate relationship between institutions, railroads, and market integration, research has expanded its scope to examine the interplay across various European countries, including Germany, with insights drawn from city-level data. A comprehensive investigation by Keller (2008) revealed that establishing railroad connections between cities substantially reduced pair-wise price disparities, underscoring railroads' instrumental role in facilitating market integration. This highlights their capacity to bridge geographical divides and harmonize economic interactions within and between regions. Germany's rail transport traces back to the 16th century with wagonways, setting the groundwork. Modern rail history began with the steam-powered Bavarian Ludwig Railway's 1835 opening between Nuremberg and Fürth, following the 1831 inauguration of the horse-drawn Prince William Railway. A milestone was the 1839 Leipzig-Dresden railway completion, Germany's first long-distance line. Rapid expansion resulted from competitive efforts by politically independent states seeking transport routes across their territories, fostering swift development (Fremdling, 1985).

Railroads had a profound impact on Prussia's economy, particularly in transporting goods like coal, construction materials, metal goods, and grain (O'Brien, 1983). However, for grain, while railroads provided a cheaper option, they couldn't match the efficiency of shipping routes. Sending grain from Posen to Cologne by train in the late 19th century was three times costlier than shipping via Rotterdam or Antwerp and navigating the Rhine (Köttgen, 1890). Long-distance grain trade along major rivers rarely used rail transport, which instead connected primary river drainage areas when sea or river transport wasn't feasible (Keller, 2008). Railroads are closely tied to industrial development, exemplified in Prussia's case. Connected cities showed larger average firm sizes, with railroads influencing industrial progress through scaling effects more than establishment numbers. Railroads also spurred urban growth by attracting migration, while fertility rates remained steady (Hornung, 2015). This underscores railroads' extensive impact on Prussia's economic dynamics, shaping both trade and industrial transformations.

In 19th-century Europe, market integration underwent profound shifts driven by a complex interplay of technological and institutional changes. Empirical analysis reveals that technological advancements had a more significant impact on market size than institutional shifts, with the decline in price gaps by approximately twenty-two percentage points serving as a crucial indicator. The synergistic effect of introducing trains, alongside currency and customs agreements, emerged as a dominant force behind reducing price gaps during this period (Keller, 2008). This underscores railways' pivotal role as bridges connecting markets and fostering economic integration. Amid the 19th century, a transition towards synchronized price movements became evident, enhancing market integration's implications by facilitating the transfer of food surpluses to regions with deficits, mitigating local supply and demand shocks, and encouraging regional specialization akin to Smithian growth (Uebel, 2011). Empirical findings unveil the contributions of different factors to reduced price gaps. Steam trains lowered gaps by around fourteen percentage points, while customs liberalizations and currency agreements each contributed about seven and six percentage points, respectively (Keller, 2008). These insights provide a comprehensive view of the intricate forces guiding market integration during this transformative era. Examining railways' influence on market integration reveals the trans-

formative power of transportation innovations in reshaping trade, prices, and economic relationships. This historical context offers valuable insights into mechanisms driving market integration, with relevance extending to modern economic dynamics.

## 1.1 Background

Prussia's 19th-century economic evolution is seen vividly through the lens of market integration. This era showcases notable shifts, with internal tariff abolishment and a unified grain market demonstrating the transformative impact of trade liberalization. Detailed price correlation analysis across commodities highlights emerging integrated markets. While initial phases show slight changes in domestic and external grain trade, accompanied by price volatility, the narrative shifts with the railway revolution from 1844. This "transport revolution" reshapes dynamics, expanding domestic grain trade and reducing price fluctuations. Railways' influence on market integration unfolds, illuminating how transportation infrastructure propelled Prussia's economic transformation during this era (Persson, 1993). Economist Friedrich List's 1841 insights highlighted railways' transformative impact on Prussia's growth. He identified advantages ranging from defense mobilization and cultural exchange to curbing scarcity and boosting economic vitality. List aptly portrayed railways as a nerve system, uniting the nation and enhancing governance, showcasing their multifaceted influence on Prussia's progress.

The Westphalian grain production scenario until 1870 illustrates the interdependent connection between railways and economic progress. Increasing grain production aligned with an integrated rye market in the 1860s, fueled by demand and efficient railways. Railways overcame waterway limitations, enabling an eightfold surge in Westphalian grain transport, especially post-1850 (Kopsidis, 2002). Investment decisions in railway projects were guided by their potential impact. Despite the intricate relationship between infrastructure and development, the transformative influence of railways on Prussia's economic growth remains evident. They bridged distances, invigorated the economy, fostered cultural exchange, and significantly influenced the nation's trajectory (Uebele, 2015).

The evolution of Prussian railways witnessed the rise of state-controlled organizations within the Ministry for Trade and Commerce, subsequently the Ministry for Public Works, overcoming initial land ownership hurdles to establish trunk lines linking major cities by the 1840s. Germany experienced swift railway growth from 2,000 km in 1845 to over 8,000 km in a decade, featuring state-owned and private entities. The groundbreaking Rhenish Railway created the first international line, connecting Cologne to Antwerp in 1843. Railroads' transformative impact extended beyond transport efficiency, influencing wages, population movement, and factors like land and housing value. The employment structure's less-explored transport influence gained significance considering weight-to-value ratios, agglomeration economies, and land's role in production (Redding, 2015).

In this context, railways can catalyze a transition away from agriculture by boosting land prices and fostering non-agricultural agglomeration economies (Bogart, 2014), while also stimulating industries through linkages and increasing demand for inputs like iron and steel (Fremdling, 1985). A comprehensive understanding of railways' impact on Prussia's economic evolution involves analyzing the shift from agriculture to industry and exploring employment dynamics within sub-industries like consumer and capital goods sectors.

Market integration in Prussia revolves around price convergence as a pivotal element for true economic cohesion, though its presence alone doesn't guarantee complete integration, given complex dynamics that can influence prices beyond transactions, potentially blurring integration boundaries (Jacks, 2003). In the context of this examination, rye emerges as a focal point due to its role as a primary bread cereal and staple food in Germany, signifying its centrality to the economy. Its widespread cultivation across Prussian regions makes rye an ideal commodity for probing market integration, unveiling the intricate interplay between staple goods, regional cultivation patterns, and broader economic interactions (Fremdling, 1979).

## 1.2 Literature Review

Technology's adoption not only has macroeconomic implications but also fosters localized advantages, driving regional growth. Yet, the challenge of establishing causality in this relationship remains. Recent studies by Atack (2010) and Duflo (2012) aim to answer whether railroads propelled growth or emerged as growth outcomes, echoing the question raised by Fishlow (1965). However, ambiguity persists in findings, underlining the intricate and multifaceted nature of this interplay.

The challenge of disentangling causality in the relationship between railways and economic development arises from the placement of railway lines, where growth-biased municipalities might secure network access, blurring railways' role as catalysts or consequences of progress (Fishlow, 1965). To address this complexity, Henderson (2005) examines Prussian city-level data. Analyzing 978 cities, the study shows that railway access significantly influenced city growth rates—an indicator of economic advancement. Cities adopting railway technology exhibited growth rates 1 to 2 percentage points higher annually than non-adopting counterparts, underscoring the role of technology in urban expansion. The complex interplay also affects the manufacturing sector. Atack (2010) explores this domain, establishing connections between railway access and the size of manufacturing enterprises from 1850 to 1870. These insights illuminate the multifaceted relationship between railways and economic evolution, highlighting the intersection of technological advancement, infrastructure access, and economic growth, each mutually shaping the other.

Reduced transport costs are widely acknowledged to enhance optimal establishment sizes through market integration and expanded market reach. The establishment of a railway network is deduced to have played a crucial role in Wurttemberg's shift from an agrarian region to an industrialized economy. The enduring economic repercussions of railway infrastructure took time to unfold, aligning with the perspective that swift transport system improvements were instrumental in 19th-century industrialization, holding relevance for the development trajectory of contemporary low- and middle-income nations (Braun, 2022).

The impact of railroad infrastructure on economic dynamics is evident through compelling findings. Proximity to railways correlates with higher GDP per capita, increased firm presence, and greater average firm profits, while also influencing income inequality in complex ways (Duflo, 2012). Railroads play a pivotal role in reducing transportation costs, affecting input prices and enhancing competition due to wider market reach, with telegraphy further accelerating communication and bridging geographical gaps (Atack,

2011). This transformation is supported by regression analysis linking pre-railroad growth to subsequent adoption, dispelling the idea that railways were solely outcomes of earlier growth, showcasing a nuanced and reciprocal relationship (Hornung, 2015).

Market integration across regions or cities holds intriguing nuances. Our analysis uncovers a systematic bias over time, as regions with similar ethno-linguistic compositions show narrower price gaps than those with contrasting compositions. These asymmetries in integration stem from ethno-linguistic networks' impact, intersecting with growing nationality conflicts and their effects on economic dynamics, highlighting the role of economic nationalism in shaping integration patterns (Schulze, 2012).

The "cultural turn" in economics offers insights into these dynamics. The study of ethnic diversity's impact shows potential erosion of trust and higher transaction costs, influencing market integration. Notably, findings highlight the dynamic nature of ethnic affiliations like Serbian or Croatian ties, which change over time rather than remaining constant across generations, emphasizing the fluidity of cultural linkages (Kala, 2021, Chilosi, 2021). Our inquiry into deviations from the Law of One Price focuses on wheat market prices across European cities, considering customs liberalizations, currency agreements, and rail transport. Our study includes pivotal factors like Zollverein liberalizations, Germany's monetary unification, and steam train advancements, each carrying weight in European economic development. Our empirical findings highlight the significance of institutional and technological change in market expansion and economic progress. Steam trains had a notable impact on reducing price gaps, especially in markets with private railways or early serfdom abolition, showcasing the interplay of historical context and transportation modes (Keller, 2008). Market integration involves two intertwined yet distinct processes: price convergence, which entails reducing price differences over time, and price adjustment, which refers to the pace of arbitraging profitable price discrepancies (Jacks, 2003). To realize the "increasing market integration" hypothesis, it requires synchronizing price fluctuations and reducing price divergence across 63 marketplaces. The significant railway construction should have prominently enhanced market integration, especially after the early 1840s (Fremdling, 1979).

This study combines modern trade literature with 19th-century economic history to explore commodity market integration determinants of that era. Distance, exchange rate volatility, language, and the border effect are crucial factors. Integration is shaped by transport, monetary regimes, commercial links, and conflicts, with trade costs more affected by monetary and policy changes than transport technology. Price adjustment speeds highlight transportation, monetary factors, and commercial dynamics' significant roles (Jacks, 2006).

### 1.3 Motivation

The story of 19th-century Prussia is characterized by market integration and commodity prices, reflecting a profound economic evolution. Our investigation centers on the convergence of commodity prices, mirroring interconnected markets during this era. Committed to historical accuracy, we explore how neighboring cities, linked by railroads, navigated dynamic economic changes. Through detailed analysis, we aim to reveal the forces shaping Prussia's cities, uncovering railroads' role in driving economic convergence. Prussia's

history unveils economic growth and the interplay of markets, prices, and railroads. Our inquiry goes beyond traditional narratives, examining price responses in nearby cities linked by railways to historical economic shocks. This study delves into interconnected dynamics, revealing how markets intertwined through commerce's locomotion, unearthing layers of history.

Undertaking an exploration of Prussia's economic landscape, the focus shifts towards evaluating the velocity of market integration, a task that demands a meticulous examination of the transformative role played by railways. With an unwavering commitment to precision, the historical context is probed to discern how neighboring cities attained economic convergence, revealing the mechanisms guiding their trajectory. Through this inquiry, the profound impact of railway development on the pace of market integration is illuminated, thereby offering fresh insights into the economic forces that molded Prussia's 19th-century narrative.

## 2 Data

### 2.1 Prussian Economic History Database (iPEHD)

This study's foundation relies on a meticulously compiled and robust dataset designed to unravel the complexities of 19th-century Prussia. The ifo Prussian Economic History Database (iPEHD) serves as the primary data source, offering county-level information encompassing a diverse range of variables that illuminate Prussia's economic landscape throughout that era. Originating from comprehensive censuses conducted by the Royal Prussian Statistical Office between 1816 and 1901, these datasets provide a wealth of county-specific insights stored within archival records. By digitizing and organizing this data, the iPEHD pioneers micro-regional empirical research in economic history, facilitating exploration of factors like education, religion, fertility, and other dimensions intricately shaping Prussia's economic trajectory in the 19th century.

The dataset comprises 343 historical Prussian counties, each possessing unique attributes in terms of size, shape, and administration. These counties have been carefully aggregated to create a coherent set of observations over time, considering the evolving nature of administrative divisions. The iPEHD dataset is organized into distinct categories, shedding light on different aspects of Prussia's economic landscape. For instance, the Education category includes data on student enrollment, teacher demographics, school types, literacy rates, and funding. The Occupation category delves into labor force details across sectors like agriculture, manufacturing, crafts, and services. Insights into wages, income tax, and income distribution are provided by the Wages and Income Tax segment. The Industry category offers information on factories, technologies, and transportation, while Agriculture provides data on livestock, crop yields, soil composition, and land distribution. Additionally, demographic dynamics like age, gender, marital status, birth and death rates, and disabilities are covered in the Population segment. The dataset also includes information on the total length of railways in each county. This comprehensive dataset forms the foundation for in-depth exploration of the complex interplay between socio-economic factors and the impact of railway development on Prussia's 19th-century economic growth and integration.

## 2.2 Historical Statistics Database (Histat)

Developed by Jürgen Sensch, Rainer Metz, and Gabriele Franzmann at GESIS, Histat came into fruition in 2004. Serving as an online platform, Histat endeavors to unlock the temporal dimensions of historical, economic, and social science research by providing access to a repository of time series datasets.

This study draws upon a diverse array of datasets housed within the Histat database, each a unique thread woven into the fabric of historical inquiry. These datasets encompass a comprehensive range of dimensions pertinent to Prussian economic and social evolution during the studied period. The datasets encompass Prussian population dynamics, the evolving expanse of railway infrastructure across Prussia, iron consumption trends across years, the proliferation of machine factories over time, international trade patterns involving Prussia, data chronicling railway and waterway freight transportation, aggregated figures for passenger and freight movement within Prussian railways, detailed records of railway-related prices, investments, and revenue in Prussia, labor statistics detailing workforce composition across different sectors (including iron and steel, construction, and textile) within various Prussian provinces and their temporal evolution, and lastly, commodity prices (including rye, wheat, barley, oats, and pork) in different cities (including Königsberg, Berlin, Hamburg, Leipzig, Köln, Mannheim, München, Memel, Danzig, Stettin, Stralsund, Thorn, Frankfurt, Magdeburg, Schweidnitz, Halberstadt, Münster, and Aachen) over time. To facilitate easy access to the datasets utilized in this study from the Histat database, the corresponding dataset codes are provided: ZA 8204, ZA 8541, ZA 8215, ZA 8245, ZA 8246, ZA 8196, ZA 8325, ZA 8277, ZA 8244, ZA 8411, ZA 8459, and ZA 8553.

## 3 Prussian Railway Evolution and Economic Impacts

In his memoirs, the Danish poet Adam Gottlob Oehlenschläger later recounted his sense of wonder during a journey on the Szczecin railway, stating: "We arrived in Szczecin at 12 o'clock to the most beautiful weather on the morning after our departure from Copenhagen. Here we saw the miracle, as this is the only possible description for one's first voyage by railway. I felt like Aladdin when he was conveyed through the air by the genie, except it was more comfortable and went up and down such a great deal" (Wolfert, 2006).

Prussia's railway revolution began with the Berlin-Potsdam Railway in 1838. State backing by 1850 expanded the network, notably benefiting the Royal Westphalian Railway Company and Prussian Eastern Railway. The Austro-Prussian War of 1866 marked a turning point for Prussian railways. The conflict allowed Prussia to take over private railways and nationalize them from 1880 to 1889. This shift from scattered private railways to a unified state-controlled system aimed at fair freight rates, distribution, and state revenue, greatly shaping Prussia's economic growth. Figure 1 visually illustrates this transformation, highlighting network and station expansion over time, showcasing how it interconnected regions and impacted Prussia's geography and economy.

Prussia's state-controlled railways drove economic growth and technological advancement. Various locomotive classes emerged, emphasizing efficiency and adaptability. This shift

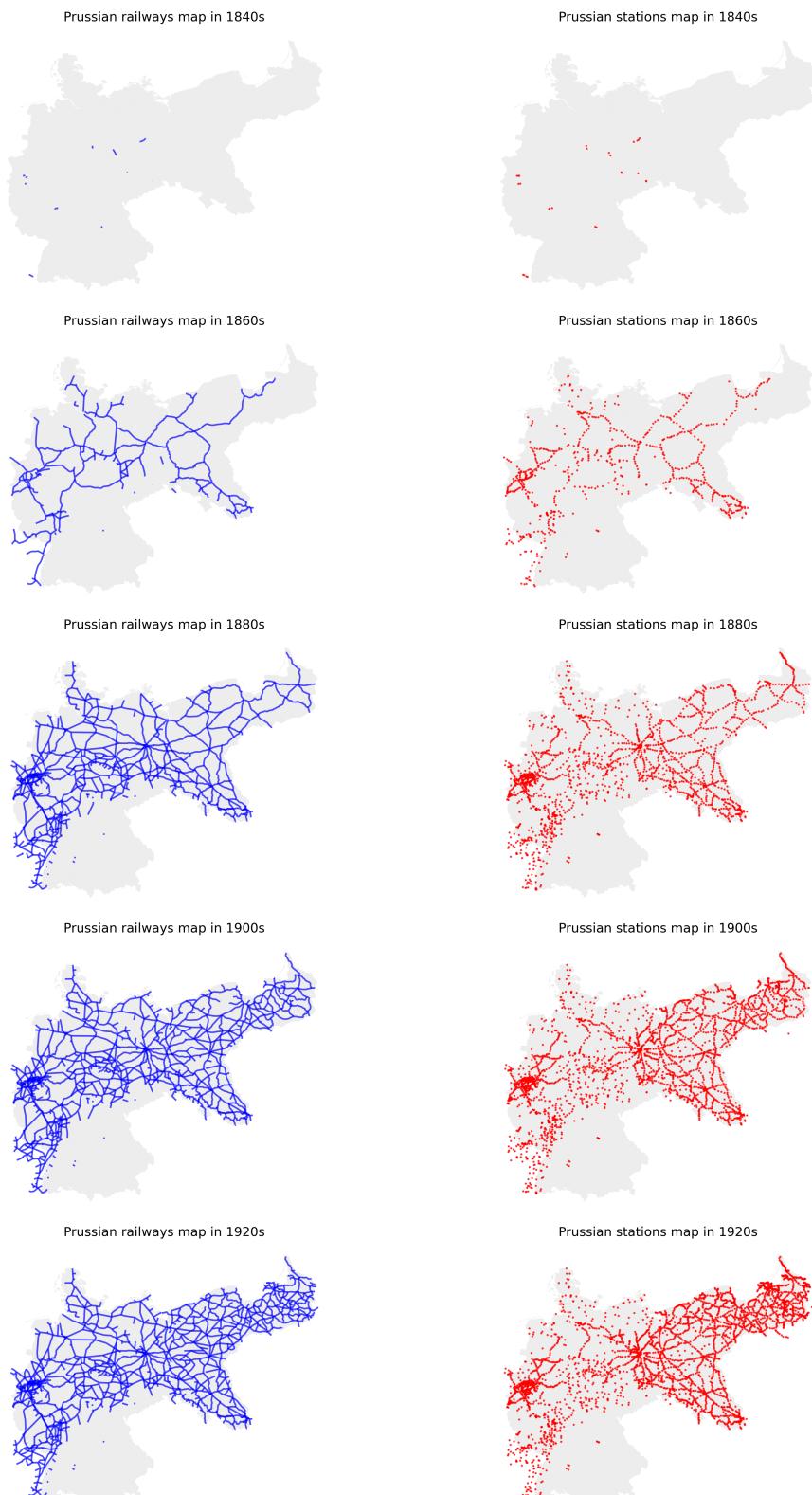


Figure 1: Prussian railways and stations maps

from private to state-run networks laid the foundation for an interconnected railway system, crucial for Prussia's industrial development. In 19th-century Europe, railways were revolutionary, transforming transportation, commerce, and urbanization, propelling Prussia and Europe into an era of unprecedented connectivity and growth.

In the 19th century, railways were instrumental in driving the industrial revolution by facilitating the swift transportation of resources and goods, stimulating productivity, trade, and urbanization. Prussia's investment in railways boosted its economic strength, positioning it as a hub for manufacturing, agriculture, and trade. Railways also had significant political and military impacts, transforming troop mobilization and promoting political integration. In Prussia, they played a pivotal role in unifying German states, leading to the formation of the German Empire in 1871. Railways also spurred technological innovation in civil engineering, metallurgy, locomotives, tracks, signaling, and safety measures, setting the stage for broader transportation advancements.

In the 19th century, Prussia's railway expansion triggered significant economic changes, driving industrialization and growth. The extensive railway network revolutionized connectivity and the movement of materials and goods, fueling industrialization and enabling access to remote resources. Efficient distribution of finished products, especially in coal, iron, steel, and machinery sectors, spurred economic growth, guiding Prussia's rise in industries and shaping its future.

Furthermore, railways had a broader societal impact by driving urbanization and population shifts in Prussia. As railway lines connected cities and towns, urban centers became economic hubs, drawing in migrants from rural areas and transforming population dynamics. The influx of urban workers fueled industrial growth, while the convenience of rail travel enhanced personal mobility, enriching leisure travel and strengthening family ties. This not only diversified labor markets but also promoted social integration and cohesion. Thus, railways went beyond physical infrastructure, catalyzing urbanization and shaping the social fabric of Prussian society during this era.

The 19th-century expansion of Prussia's railway network had profound effects on both its economy and society. It significantly boosted industrialization by efficiently transporting materials, goods, and people, particularly benefiting steel, machinery, coal, and iron industries. This accelerated economic growth and solidified Prussia's position as a leading European industrial power. Beyond industry, the railways played a key role in urbanization, attracting rural populations to thriving urban centers. They also facilitated personal mobility, enabling leisure travel, family connections, and diverse labor markets, contributing to a more integrated and dynamic Prussian society that enriched both the economic and social landscape.

Prussia's 19th-century railway expansion revolutionized labor mobility and specialization. It enabled laborers to move to regions where their skills were in demand, addressing industry-specific labor shortages and promoting specialized sectors. This ease of travel encouraged regions to develop industries that aligned with their strengths and resources, fostering diversity and interconnection within the economy. Railway development spurred infrastructure growth by requiring large-scale production of steel, machinery, and construction materials. This demand led to the establishment of industries supporting railway expansion, with steel mills and quarries supplying rails, locomotives, stone, and gravel. As these ancillary industries grew, a network of suppliers and service providers emerged,

generating economic activity and jobs. This symbiotic relationship between railways and supporting industries was crucial for Prussia's economic progress, setting the stage for modern infrastructure and prosperity.

Beyond connectivity, railways transformed the speed and scale of trade. Swift and reliable rail transport revolutionized commerce, reducing costs and enhancing efficiency. Prussian industries excelled domestically and internationally, adapting to market shifts and consumer preferences. Railways bridged ports and inland cities, facilitating the movement of imported goods, expanding trade, and consumer choices. Imported products fueled consumerism, boosting economic growth. This cycle of increased production, consumption, and market expansion defined Prussia's economic transformation. Railways fundamentally reshaped market integration, erasing geographical barriers, stimulating specialization, and driving industrialization and economic progress during the 19th century.

### 3.1 Impacts of Railway Development on Industrialization and Population

In 19th-century Prussia, the expansive railway network transformed industry and population patterns. Railways broke down geographical barriers, accelerating the movement of goods and people. This efficiency fueled industrial growth by providing access to resources and markets. Factories thrived, thanks to rapid product distribution. Railways not only transported goods but also drove progress, giving rise to vital industries like steel and machinery, essential for Prussia's economic success.

Railway expansion drove urbanization as people moved from rural to urban areas for jobs and better lives. Cities became economic hubs, attracting a diverse workforce. Railways also connected regions, fostering cultural exchange and innovation. Remote villages gained access to markets and services, transforming their prospects. This reshaped settlement patterns and created a socially dynamic landscape with changing opportunities and aspirations.

Figure 2 vividly illustrates the close link between railway development, population growth, and their transformative impact on Prussia. In 1840, with minimal railway infrastructure, Prussia had under 35 million people. By 1910, as railways expanded to over 45,000 kilometers, the population soared to over 65 million.

This visual representation depicts the intertwined growth of railways and population. The simultaneous rise in both demonstrates their mutual influence. Railways enhanced connectivity, driving urbanization and industry, which, in turn, attracted more people to cities. The growing population, in need of efficient transport, fueled railway expansion into new areas. The graph captures this crescendo of progress, symbolizing a nation's evolution along iron tracks.

Figure 3 offers a revealing look at Prussia's transformation from 1830 to 1870. By overlaying maps of annual railway length and population density, the figure highlights their interdependence. Bold-outlined counties indicate higher indexes, emphasizing railways' significant impact on the landscape and population distribution. The merging of railway networks and denser populations tells the story of modernization, showcasing how railways drove industrialization, urbanization, and societal change during this critical era.

Railway development greatly influenced industrialization. It drove demand for materials,

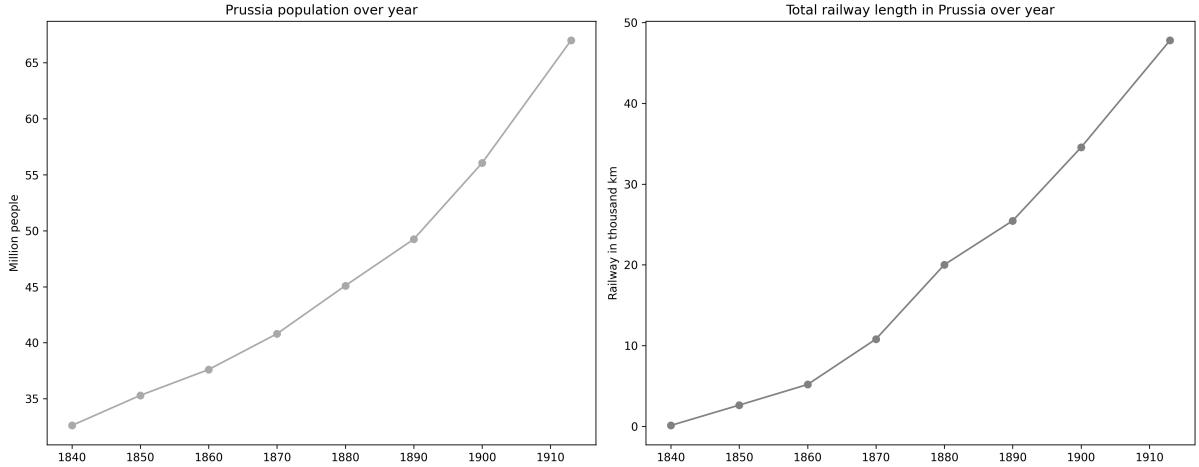


Figure 2: Total Prussia population and total railway length

machinery, and skilled labor, benefiting engineering and manufacturing sectors. Industries producing steel, locomotives, tracks, and related equipment thrived, expanding the rail network. Railway construction also led to innovation and modernization in various industries. Railway development indirectly drove industrialization by improving transportation and connectivity. Efficient railway transport reduced costs, extended market reach, and stimulated trade, creating a cycle of increased demand, production, and industrial growth. This led to regional specialization and a more diversified and integrated economy. Railways also revolutionized supply chains, making goods more accessible and fostering industrialization. Additionally, they facilitated the flow of ideas and innovations, speeding up the spread of knowledge and technology, boosting productivity and economic growth. In essence, railways acted as catalysts for industrialization, shaping the economic landscape directly and indirectly.

The swift evolution of industrialization in 19th-century Prussia is vividly represented by two key indicators showcased in Figure 4: the Consumption of Iron and the Number of Machine Factories. These figures provide a glimpse into the remarkable pace at which industrialization unfolded during this era.

The Iron Consumption graph shows a significant spike in iron usage, a vital resource for industrial production. Consumption went from about 0.4 million tons in 1850 to over 1.8 million tons by 1870, reflecting increased demand for raw materials driven by expanding industrial activities. This rise in iron consumption correlates with heightened production of goods, infrastructure, and machinery, key elements of industrialization. The Number of Machine Factories chart demonstrates rapid industrialization. In 1845, Prussia had fewer than 500 machine factories, indicating limited industrial presence. By 1875, this number exceeded 2,500, indicating exponential growth in factories equipped with machinery. This growth reflects the adoption of mechanization, turning Prussia into a manufacturing and innovation center. It also signifies advanced technology integration, a critical factor in regional industrialization.

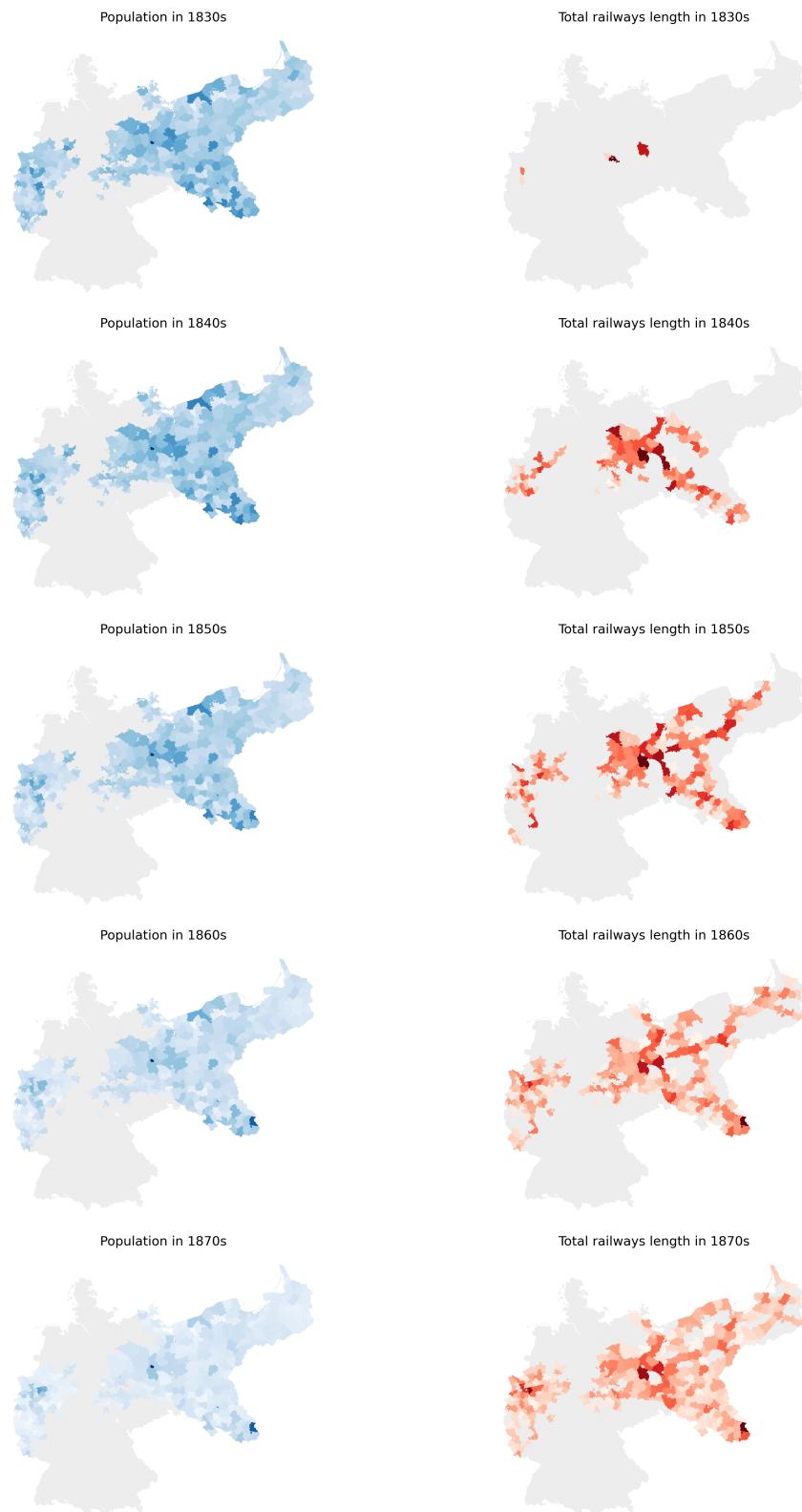


Figure 3: Relative maps of average annual railway length in kilometers and average population in Prussia (1830-1870 decades), bolder counties mean greater relative indexes

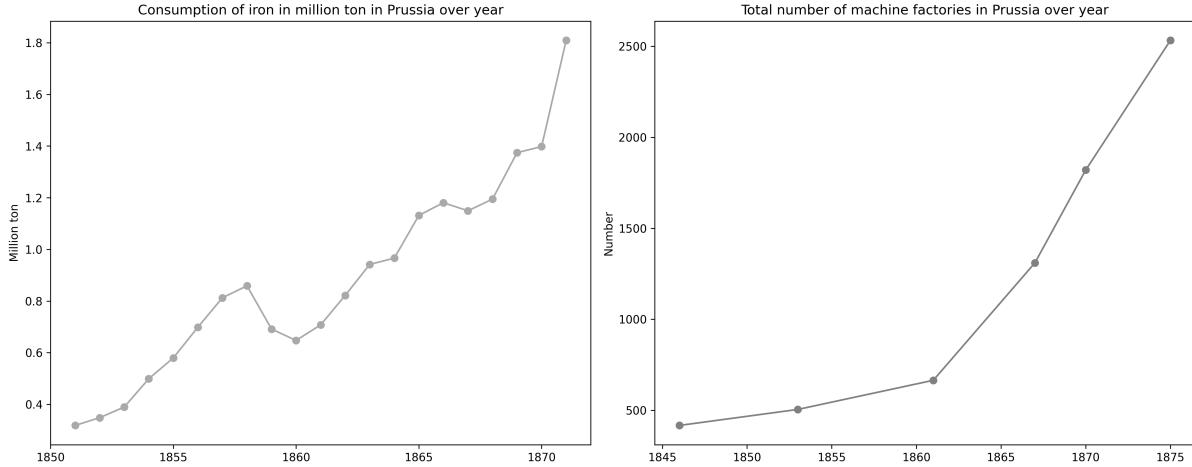


Figure 4: Consumption of iron and number of machine factories in Prussia

### 3.2 Impacts of Railway Development on International Trade

Railway development significantly boosted international trade, connecting Prussian industries to global markets. This infrastructure streamlined cross-border exchanges, promoting economic interdependence and elevating Prussia's international standing. Figure 5, showing Prussia's International Trade Imports and Exports, visually demonstrates the transformative impact of railway development on the nation's economy. The simultaneous increase in both imports and exports during the railway expansion era highlights how railways facilitated international trade. This interconnected railway network enabled efficient long-distance goods transport, empowering Prussia to engage more actively in global trade. The parallel growth in imports and exports reflects the railways' pivotal role in expanding Prussia's trade, elevating its international trade status.

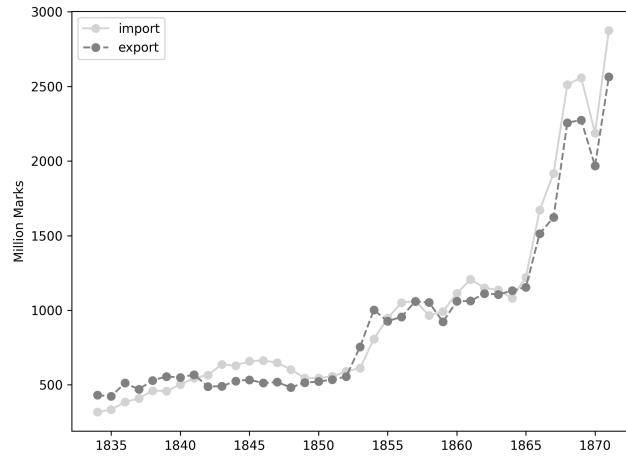


Figure 5: International Trade Imports and Exports of Prussia

Figure 6, illustrating the Percentage of railway freight share in total transport (railway

and waterway) in Prussia, showcases the transformative impact of railways on transportation. The graph reveals a direct link between railway expansion and the share of railway freight in total transport. As railways extended and connected cities, the railway freight percentage steadily increased. The stability around 80 percent by 1900 signifies extensive railway development, establishing railways as the dominant mode of transport. This shift also affected waterway transport, with more freight arriving at sea ports and using waterways for further transport. This dynamic relationship underscores how railway development profoundly shaped Prussia's transportation landscape.

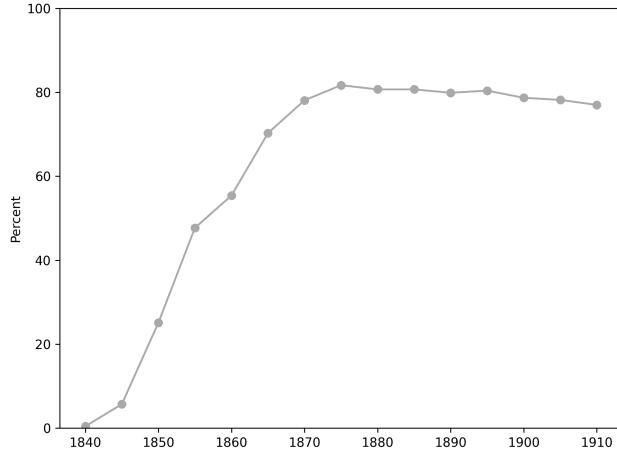


Figure 6: Percentage of railway freight share in total transport (railway and waterway) in Prussian region

### 3.3 Impacts of Railway Development on Inland Locomotion

Railway development had a profound impact on internal transportation in Prussia. The widespread railway networks revolutionized both passenger and freight travel. Rail travel's efficiency and convenience transformed the speed and reach of transportation, surpassing traditional methods. This improved accessibility not only drove economic growth but also enhanced labor mobility, enabling workers to move across regions for job opportunities and creating a more adaptable and dynamic labor market. Furthermore, railways played a key role in immigration by facilitating the movement of people to growing industrial cities. They also efficiently transported essential goods over long distances, bridging regional disparities and fostering economic interconnectedness in Prussia. This extensive railway network served as conduits for both people and goods, significantly influencing labor trends, migration patterns, and trade dynamics throughout the region.

Figure 7, illustrating passenger and freight traffic on Prussian railways, encapsulates the remarkable transformation wrought by railway development. The surge in passenger traffic from under 6,000 million passenger kilometers annually in 1880 to over 40,000 million passenger kilometers annually highlights the profound effect of railways on mobility. This

exponential growth underscores the newfound accessibility and convenience that railways provided, enabling people to travel long distances with unprecedented ease.

Simultaneously, Figure 7 also portrays the remarkable surge in freight traffic, with the annual movement of goods escalating from around 10,000 million ton kilometers in 1880 to an astonishing 60,000 million ton kilometers by 1910. This surge in freight movement epitomizes the pivotal role of railways in enabling efficient and extensive trade across the Prussian landscape. By connecting production centers with distribution hubs and ports, the railways not only facilitated the movement of raw materials and finished products but also played a crucial role in shaping the industrial and economic landscape of Prussia during this transformative era.

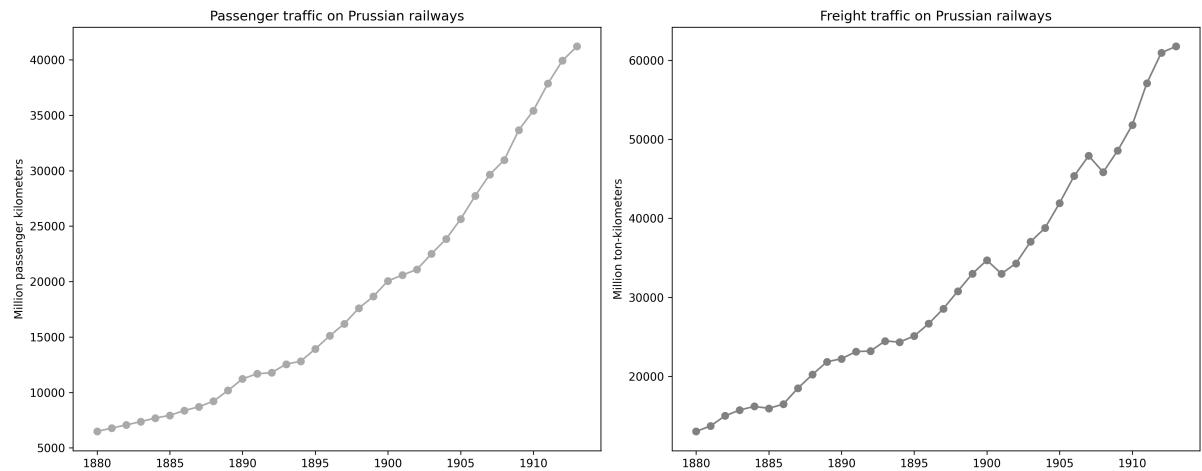


Figure 7: Passenger and freight traffic on Prussian railways

Figure 8 illustrates average annual output growth rates for passenger and freight railway transport in Prussia, highlighting the profound impact of railway development on transportation dynamics and the economy. The remarkable growth rates of around 60 percent for ton kilometers of freight and passenger kilometers in 1845 emphasize the transformative influence of railways. This rapid growth was facilitated by economies of scale, enabling efficient and economical movement of goods and people across extensive distances. This marked a new era where transportation of freight and passengers transcended the constraints of earlier modes of travel.

Figure 8 shows changing growth patterns. After 1875, passenger kilometers' annual growth stabilized below 10 percent, indicating a mature phase in passenger transportation. A similar trend appears for freight ton kilometers, with a more noticeable decline. This reflects an evolving industrializing Prussian economy, where efficient transportation of passengers and goods remained essential for growth and economic progress.

Figure 9, displaying average railway transport prices for passenger-kilometers and ton-kilometers in Prussia, tells a compelling story of how railway development transformed transportation affordability. In 1840, passenger kilometers cost over 4 marks, while freight transport was around 18 marks. However, as the railway network expanded and technology advanced, significant price shifts occurred. Over time, both passenger and freight transport costs notably decreased, reflecting improved infrastructure, operational effi-

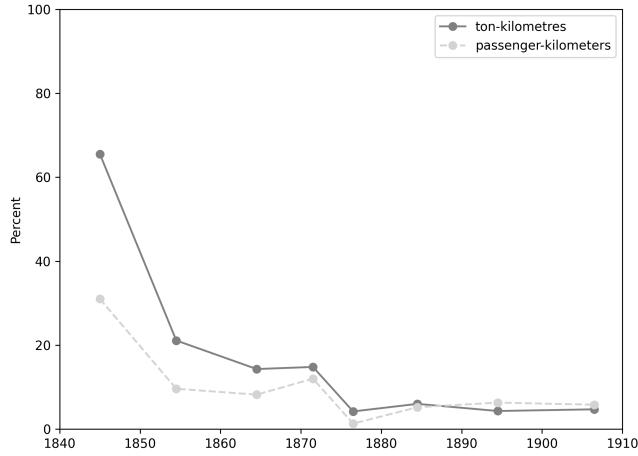


Figure 8: Average annual output growth rates (in percent) for passenger and freight railway transport in Prussia

ciency, and economies of scale as the railway system matured. By 1880, passenger kilometer costs were below 4 marks, and freight transport prices had dropped to under 5 marks.

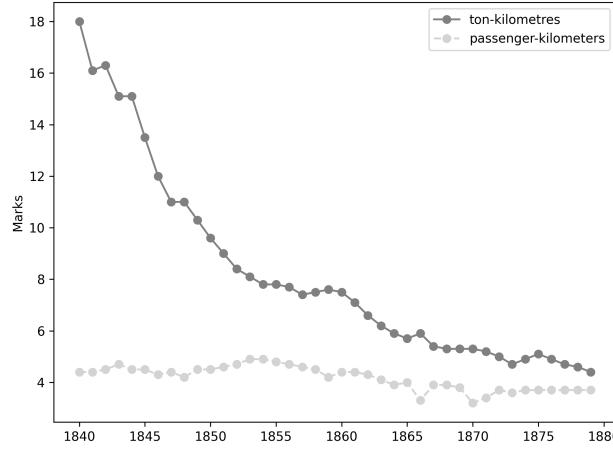


Figure 9: The average railway transport price for passenger-kilometers and ton-kilometers in Prussia

As the railway system matured, both passenger and freight transport prices significantly decreased. This underscores the transformative impact of railway development on Prussia's economy, as railways adapted to changing demands, initially prioritizing passenger travel and later making freight transport more affordable. This evolution highlights the railways' role in facilitating efficient movement of people and goods across Prussia.

### 3.4 Impacts of Railway Development on Labor

The impacts of railway development on labor in 19th-century Prussia were profound and multifaceted, fundamentally reshaping the landscape of work and employment. As railways expanded across the region, they generated a ripple effect on labor dynamics through various channels.

The construction and upkeep of railways required a diverse labor force, from skilled engineers to manual laborers, creating abundant job opportunities. Additionally, auxiliary industries like steel production, iron mining, and timber harvesting, born from railway construction, further bolstered employment across sectors. Railways facilitated labor mobility between regions with varying workforce availability, encouraging industry specialization, economic growth, and diversification. They also promoted knowledge sharing, disseminating industrial techniques, scientific advancements, and manufacturing processes, fostering innovation and contributing significantly to Prussia's industrial advancement.

Market integration through railways profoundly influenced labor migration patterns. Specialized industries in different regions attracted workers seeking employment opportunities, leading to the growth of cities with comparative advantages in sectors like manufacturing, textiles, and mining. For example, coal-rich cities became hubs for industries like steel production. Railways connected these cities to resource-deficient regions, facilitating worker access and skill distribution, ultimately boosting productivity. Railways also streamlined the transportation of raw materials and goods between cities, enhancing interconnected supply chains. Specialized cities became essential nodes in a larger economic network, promoting synchronized labor and resource distribution, and driving economic growth.

Figure 10 depicting the coefficient of variation of monthly wages among different provinces in Prussia offers valuable insights into the dynamics of labor wages across various sectors and regions. The coefficient of variation quantifies the degree of dispersion in wages among different provinces, reflecting the extent of wage inequality within specific industries over time.

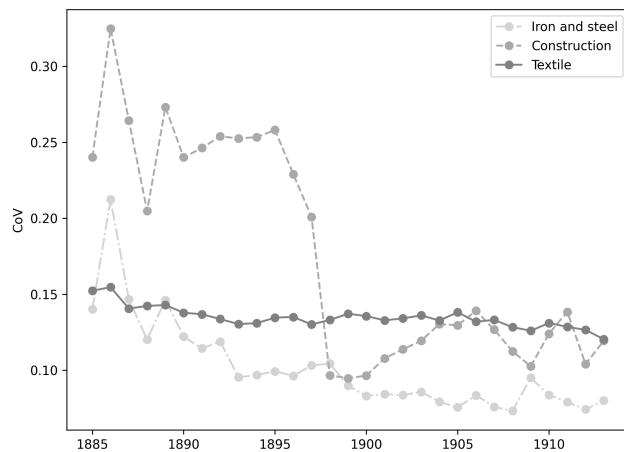


Figure 10: Coefficient of variation of monthly wages among Prussian's different provinces

The three distinct lines on the Figure 10 correspond to the textile, iron and steel production, and construction sectors. These sectors were critical drivers of industrialization and economic growth during the 19th century. The data captured over a span of years and across approximately 10 different provinces in Prussia provide a comprehensive picture of wage variations.

Laborers often prioritized employment decisions based on relative productivity advantages, seeking higher wages in provinces with thriving industries. The Coefficient of Variation, a wage distribution disparity metric, reflected wage equality among provinces. The expanding railway network fostered a more interconnected labor market, reducing wage disparities, as shown in the graph. However, it's important to note that regional productivity differences, maintaining relative advantages and higher wages in specific provinces, prevented the coefficient of variation from reaching zero.

### 3.5 Railway Financial Prospects and Returns

The Prussian railway industry had diverse financial impacts on the economy. It directly generated employment and contributed to economic output. Indirectly, it boosted trade, innovation diffusion, and industry mobility, fueling economic growth. By efficiently connecting regions and facilitating the circulation of goods, railways expanded Prussia's GDP, emerging as a significant driver of 19th-century economic development. Figure 11 depicts the financial importance of railways through the percentage of Passenger Transport Revenue in total passenger and freight revenue. The data shows that passenger transport revenue consistently accounted for approximately 30 percent by 1875, emphasizing the vital role of passenger transportation in the railway revenue structure and the growing demand for efficient travel options. This underscores the railway network's social and economic significance.

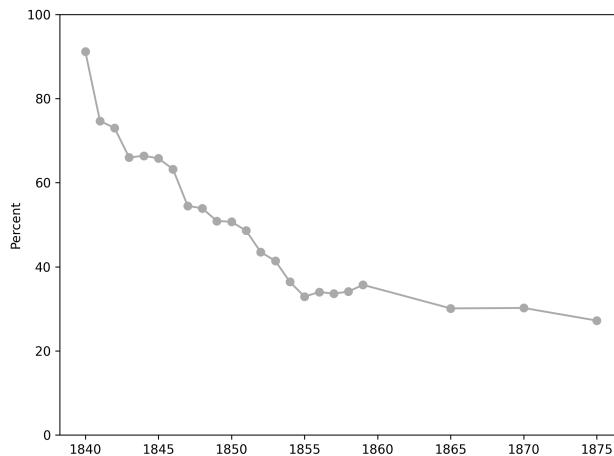


Figure 11: Passenger transport revenue as a percentage of total passenger and freight revenue

Figure 12, depicting Revenue from Passenger and Freight Traffic on Prussian railways

compared to Total Investment, offers insights into the railway industry's financial dynamics. Over time, a clear trend emerges where revenue from freight traffic consistently outpaces passenger revenue. This gap underscores the significant contribution of freight transportation to the financial sustainability of the railway system. The graph also shows a consistent increase in railway investments, reflecting a commitment to expanding and upgrading infrastructure for both passenger and freight transport. This growing investment signifies efforts to enhance the railway network's capacity and efficiency, leading to higher revenue. The interplay between revenue trends and investment emphasizes the railways' pivotal role in driving economic growth and development in Prussia's evolving industrial landscape.

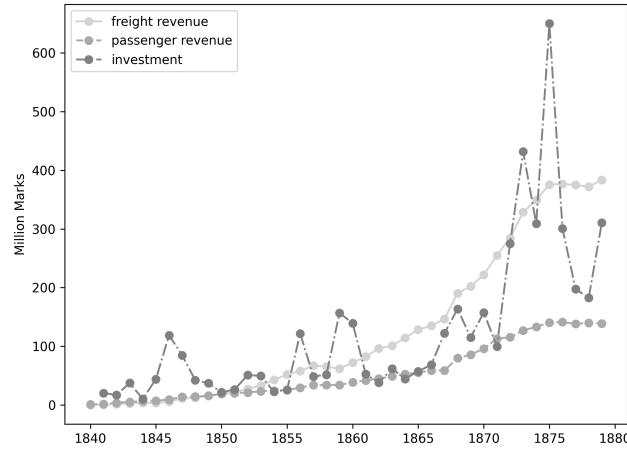


Figure 12: Revenue from passenger and freight traffic on Prussian railways compare with total investment on railways

## 4 Methodology

### 4.1 Railway Distance Estimation

This section introduces a novel methodology for the estimation of travel distances between diverse cities within the Prussian railway network. This estimation approach hinges on the integration of historical railway data and graph theory algorithms, aimed at capturing the temporal evolution of travel distances influenced by the inception and cessation of railway lines.

To accomplish this objective, a comprehensive dataset encompassing the geographic coordinates of railway stations, the railway map, and the specific years of inauguration or discontinuation of stations and railway segments was employed. This dataset serves as the cornerstone for our estimation procedure, facilitating the construction of a dynamic model that portrays the progression of the railway network's configuration over time, as expounded upon in Appendix B.

A pivotal component of our methodology entails the utilization of Dijkstra's Shortest Path Algorithm, a widely recognized graph theory technique. This algorithm adeptly identifies the optimal travel route between any pair of cities by assessing the cumulative travel duration across distinct sections of the railway network. Critically, the algorithm accommodates the historical context by incorporating the opening and closing years of railway lines. This ensures that the computed travel distances accurately mirror the accessibility and interconnectivity of cities during specific temporal intervals.

Our approach amalgamates spatial and temporal dimensions, enriching our comprehension of the evolving travel distances within Prussia's railway network. By synergizing historical railway data with advanced graph theory algorithms, we achieve the quantification of the influence of railway expansion on travel distances over an extensive span of decades.

## 4.2 Measuring Market Integration

Market integration is the idea that various markets, regardless of geographical or institutional boundaries, are interconnected to form a unified entity. It involves breaking down barriers to trade and commerce, enabling the seamless flow of goods, services, and information. Market integration can occur at different levels, from local to global, and is closely linked to globalization, where economies and societies become more interdependent. Market integration is the harmonization of economic activities to enable the exchange of goods and services across regions. It's driven by technology, improved infrastructure, and favorable trade policies. The goal is to encourage the unrestricted movement of resources, fostering economic growth and allowing countries to utilize their strengths more broadly. Market integration also has impacts on social and political dynamics.

In this study, the main objective is to measure market integration levels within the Prussian region. This involves a detailed analysis of historical data and economic indicators to quantify how interconnected Prussian markets became over time. It includes examining trends in trade volume, the alignment of prices, and economic policies across different cities and provinces in Prussia. Through these quantitative assessments, we aim to gain valuable insights into the impact of railway development and other factors on the degree of market integration in the Prussian economy.

### 4.2.1 Law of One Price

The concept of market integration, as defined by Fremdling, embodies a temporal process that fosters an economic interrelationship among geographically distinct markets. This definition's emphasis on economic interdependence is pivotal to its theoretical scrutiny, which can adopt either a static or dynamic perspective (Fremdling, 1979). For the present study, we adopt a static stance, entailing the analysis of spatial price level convergence over time, often referred to as the law of one price (LOP).

The law of one price postulates that in integrated markets, prices of identical goods align uniformly. This economic principle underscores that within interconnected markets, the pricing of identical commodities attains uniformity. Hence, the LOP serves as a benchmark to assess the extent of market integration, providing insights into the harmonization of price levels across spatially separated markets. To apply this theory to spatial trade, it is necessary to account for transport costs through the following equation:

$$P_i = P_j + T_{ij} \quad (1)$$

In this equation,  $P_i$  represents the commodity price in market  $i$ ,  $P_j$  denotes the commodity price in market  $j$ , and  $T_{ij}$  represents the transport costs associated with moving goods between markets  $i$  and  $j$  (commodity prices). Assuming a unidirectional flow of goods from market  $j$  to market  $i$ , the aforementioned equation signifies that the price in market  $i$  equals the price in market  $j$  plus the relevant transport costs. This equilibrium condition is sustained through arbitrage forces. Firstly, if the price of a particular commodity in market  $i$  surpasses the price of the same commodity in market  $j$  plus the transport costs, informed traders can profit by transporting goods from market  $j$  to  $i$ . This increase in supply reduces prices in market  $i$  and elevates prices in market  $j$  due to decreased supply. Secondly, if the left side of the equation is lower than the right side, it signifies a decrease in demand for products from market  $j$ . Consequently, there is an increase in prices in market  $i$  due to supply scarcity and a decrease in prices in market  $j$  attributed to reduced demand. If trade occurs bidirectionally, the Law of One Price (LOP) can be defined as:

$$|P_i - P_j| \leq T_{ij} \quad (2)$$

When price disparities exceed transport expenses, arbitrage activities occur until these disparities become equal to or less than the transport costs. Conversely, if price differences are lower than transport costs, trade remains inactive due to self-sufficiency in both regions. If a third market  $k$  is introduced, with goods flowing from  $i$  to  $j$  and from  $k$  to  $j$ , the LOP can be extended the following condition needs to be satisfied:

$$|P_i - P_k| \leq |T_{ij} + T_{kj}| \quad (3)$$

#### 4.2.2 Coefficient of Variation & Variance of Relative Prices

##### Coefficient of Variation:

A practical way to put the Law of One Price into action and track its changes over time is to use a measurement called the coefficient of variation (CoV). This measure helps us understand how prices of goods in different cities compare to each other. It's like looking at the "spread" of prices. The CoV is found by dividing the standard deviation (a measure of how much the prices vary) by the average (the typical price) of all the prices in a particular year. Here's how we calculate it:

$$\text{CoV}_t = \frac{\text{SD}_t}{\mu_t} = \sqrt{\frac{1}{N} \sum_{i=1}^N (x_{it} - \mu_t)^2 / \mu_t} \quad (4)$$

In this formula,  $x_{it}$  is the price of a certain type of grain in the city  $i$  during the year  $t$ , and  $\mu_t$  is the average price of that grain across all the cities in that same year  $t$ .  $N$  is the total number of observations we have. The CoV helps us see how much the prices in different cities "spread out" from the average. If the CoV is small, it means that prices are pretty similar across cities, suggesting a strong connection between markets. On the other hand, if the CoV is large, it means that prices are more spread out, showing less connection between markets.

### Variance of Relative Prices:

The concept of market integration is often examined using a variety of metrics in contemporary economic literature. One such measure, extensively utilized by researchers like Engel and Rogers (1995), is the variance of the logged relative price over a specified time horizon. This measure, denoted as  $V_{ijT}$ , serves as a valuable tool for assessing the level of market integration between two cities, labeled as  $i$  and  $t$ , over the time period  $T$ , as follow:

$$V_{ijT} = \text{Var}(\ln(\frac{P_{iT}}{P_{jT}})) \quad (5)$$

The metric captures how relative prices of similar goods or commodities between these cities evolve over time. In a highly integrated market, prices of identical or comparable items in different cities tend to move closer together, indicating a convergence of prices. This convergence reflects efficient market interactions and reduced price disparities. Conversely, in less integrated markets, larger price differences between cities can indicate limited coordination and potentially higher trade barriers. The essence of the measure lies in its capacity to quantify these price dynamics. A smaller value for the variance suggests that relative prices between the cities are tightly clustered around their average, signifying strong price convergence and robust market integration. Conversely, a larger value implies that relative prices are more dispersed, pointing to price divergence and weaker market integration.

## 4.3 Assessing Railway's Impact on Market Integration

The connection between railway development and market integration is intricate and has profound economic consequences. Railway systems can greatly affect market integration through various channels, primarily related to commodity prices. This section seeks to delve into these channels and clarify the criteria used to assess the influence of railway development on market integration. Railway development significantly impacts market integration by reducing transportation costs. Railways connect distant cities, providing a cost-effective means of transporting goods. This cost reduction encourages cross-regional trade and contributes to the alignment of commodity prices across markets. Railway connectivity facilitates the movement of goods, strengthening economic connections and potentially leading to a more integrated market.

Improved access to market information through railway networks is another crucial channel. Efficient transportation enables rapid dissemination of market data, including prices, demand, and supply. This transparency empowers market participants to make informed decisions, adapt to changing conditions, and capitalize on profit opportunities across regions. Consequently, enhanced market information can lead to reduced price disparities and foster a more integrated market structure.

When assessing the impact of railway development on market integration, specific parameters serve as essential indicators. Notably, the decrease in travel time between cities due to railway expansion plays a crucial role. The reduction in travel time signifies improved accessibility and connectivity, which can lead to increased trade interactions and ultimately contribute to market integration. Furthermore, the alignment of commodity

prices across regions is a key metric for evaluating market integration. The variance of logged relative prices over time serves as a quantitative measure of price convergence. A decrease in the variance of these prices suggests that the impact of railway development on market integration is positive, as prices across markets are converging, indicating a higher level of economic interconnectedness.

#### 4.3.1 Panel Data Analysis

Central to the scope of this study is the endeavor to quantify the influence exerted by railway development on the integration of markets, with a specific focus on the evolving convergence of commodity prices among diverse cities. The underlying inquiry pertains to the degree to which the establishment of railways, leading to reduced temporal distances between cities, corresponds to a discernible reduction in price discrepancies. To navigate this intricate relationship, our analytical framework employs a fixed-effects estimator, strategically excluding city-specific and year-specific fixed effects from the equation. This selective omission aims to isolate the intrinsic impact of distance on price disparities, thus disentangling it from broader contextual influences.

#### Fixed Effect Estimator:

The approach undertaken herein seeks to unravel the intricate connection between the expansion of railways and the phenomenon of market integration, specifically through the lens of diminishing time distances and their potential impact on price convergence across cities. To address this inquiry, a fixed-effects estimator is employed, adeptly mitigating the potential effects stemming from variations at the city and year levels. The analytical focus remains on the logarithmic deviations in prices, thereby enabling the isolation of the distinct role played by changing distances, independently of other potential confounding factors. This methodological pursuit is expected to yield a quantifiable assessment of the impact of railway development on the intricate dynamics of market integration. By engaging in this systematic analysis, valuable insights are anticipated to emerge, elucidating the extent to which enhanced transportation infrastructure fosters a more harmonized and integrated market environment. Transitioning to the focal point of investigation, the following equation sheds light on the intricate connection between railway development and market integration:

$$|\ln\left(\frac{P_{it}}{P_{jt}}\right)| = \alpha \ln(D_{ijt}) + \sum_{m=1}^N \beta_m Z_m + \sum_{t=t_0}^T \gamma_t Z_t + \epsilon_{ijt} \quad (6)$$

The equation provided encapsulates the dynamics of market integration in the context of railway development. The metric  $|\ln(P_{it}/P_{jt})|$  represents the logarithmic price difference between a commodity in cities  $i$  and  $j$  at time  $t$ . The coefficient  $\alpha$  quantifies the impact of distance on market integration. The term  $\ln(D_{ijt})$  reflects the logarithmic distance between cities  $i$  and  $j$  during time period  $t$ , considering the evolving connectivity from railway expansion. The equation also incorporates year-specific dummy variables  $Z_t$  and city-specific dummy variables  $Z_m$  to control for year and city fixed effects, respectively. This equation collectively assesses how distance, influenced by railway development, inter-

acts with other factors to shape commodity price convergence or divergence across cities over time.

### **Engel (1995) Estimator:**

An alternative method to assess the dynamics of market integration involves examining the variability in prices over a specific time interval. While some researchers have approached the investigation of market integration using gravity-model-inspired frameworks, another avenue of analysis delves into the fluctuations of prices across time horizons. This approach aims to capture the temporal volatility in price differentials between cities and offers additional insights into the evolving interdependence of markets. One such analytical path is embodied by the equation:

$$V_{ijT} = \alpha \ln(\bar{D}_{ijT}) + \sum_{m=1}^N \beta_m Z_m + \epsilon_{ijT} \quad (7)$$

This model, which draws inspiration from the seminal work of Engel and Rogers (1995), showcases how variations in price over time can be utilized to gauge market integration dynamics. In this equation,  $V_{ijT}$  represents the variance of the logged relative price between cities  $i$  and  $j$  over a specific time horizon  $T$ . The coefficient  $\alpha$  quantifies the impact of the average distance  $\bar{D}_{ijT}$  on the variability in price differences. The inclusion of city dummy variables  $Z_m$  allows us to control for city-specific fixed effects, providing a way to mitigate the influence of local idiosyncrasies on price variation. The residual term  $\epsilon_{ijT}$  captures unobserved influences that may affect price volatility.

### **Estimator Based on CoV:**

To bolster the robustness of our findings, we explore the relationship between country-level railway development (represented by total railway length) and the extent of price convergence across entire regions. This entails assessing how variations in total railway length within Prussia relate to deviations from average prices across different cities. For this evaluation, we employ the Coefficient of Variation (CoV), a reliable metric showcasing price spread from the mean over time. The CoV's significance lies in its ability to illustrate price variability. A smaller CoV indicates greater price uniformity among cities, signifying robust market interconnections. Conversely, a larger CoV implies wider price discrepancies, reflecting weaker market linkages. By utilizing the CoV, we gauge how changes in total railway length, reflecting railway development, influence the level of price convergence across distinct Prussian regions, thereby fortifying the insights drawn from our analysis. This approach resonates with the pioneering work of Engel (1995) and enhances the comprehensive exploration of the intricate interplay between railway expansion and market integration. Transitioning to our exploration of the Coefficient of Variation (CoV) in the context of railway development, the estimator below is suggested: The equation

$$\text{CoV}_T = \alpha \ln(L_T) + \epsilon_T \quad (8)$$

depicts the relationship between the Coefficient of Variation (CoV) and log of the total length of railways ( $L$ ) in Prussia during time  $T$ . Here, the CoV offers insights into the

variation of prices across Prussian markets at time  $t$ , while  $L$  quantifies the extent of railway development at the same time. The term  $\epsilon_T$  accounts for the unobserved error.

#### 4.3.2 Callaway & Sant'Anna's DiD Estimation

Traditional Difference-in-Differences (DiD) analysis, a prevalent econometric method, assumes a consistent treatment effect over time and across all units, which can be overly simplistic for policies with evolving impacts or variable timing of implementation. This limitation poses challenges when estimating causal effects accurately. However, a novel estimator introduced by Callaway and Sant'Anna (2021) departs from the traditional DiD's uniform treatment effect assumption, enabling researchers to uncover nuanced dynamics and produce more accurate estimates that align with the complexities of real-world policy interventions.

Callaway and Sant'Anna's estimator, in contrast to traditional DiD, accommodates the intricate nature of policy impacts over time. By recognizing distinct comparison groups for each cohort of treated units, the estimator prevents bias that can arise when treating all units equally. This refinement is particularly crucial in scenarios where units experience treatment at different points in time. In Appendix C, there is a supplementary elaboration on the operational mechanics of this innovative difference-in-differences estimator.

Through the utilization of the innovative difference-in-differences (DiD) estimator, the investigation of the ramifications associated with the incorporation of cities into the railway system becomes attainable. In this context, the integration of cities with the railway system is treated as a binary variable, signifying the treatment allocated to cities at distinct temporal junctures. The application of this estimator facilitates the examination of the influence exerted by the interconnection of cities via the railway system, encompassing an analysis of its repercussions on market price integration. This entails an assessment of the extent to which convergence is observed in commodity prices across diverse cities over a span of time, thereby elucidating the role of the railway network in fostering market integration. Employing this methodology affords insights into the manifold effects of railway connectivity on economic interactions and the evolving dynamics of markets among cities. Thus, the baseline analysis comes from the following regression:

$$|\ln\left(\frac{P_{it}}{P_{jt}}\right)| = \alpha R_{ijt} + \sum_{m=1}^N \beta_m Z_m + \sum_{t=t_0}^T \gamma_t Z_t + \epsilon_{ijt} \quad (9)$$

This regression closely resembles the conventional fixed effect estimator, distinguished by the incorporation of the variable  $R_{ijt}$ , a binary indicator denoting the connection between cities  $i$  and  $j$  via the railway system in time  $t$ . Applying the methodology introduced by Callaway and Sant'Anna, the investigation entails the evaluation of the impact of railway connectivity on market integration, specifically focusing on the average treatment effect.

### 4.4 Railway's Effect on Labor Harmonization

Labor harmonization, in the context of market integration and commodity prices, aims to establish uniform labor standards and practices. This synchronization of labor conditions reduces disparities in production costs and wages, leading to greater price convergence

for goods. Harmonizing labor practices fosters fair competition, enhances market efficiency, and contributes to the overall integration of economies, stabilizing commodity prices across regions.

Railway development has a multifaceted impact on labor dynamics, affecting wages and labor mobility. It can increase labor demand in regions by improving connectivity to markets and resources, potentially raising wages. This is especially notable where railways facilitate the movement of both goods and labor, leading to higher demand for workers of various skill levels. Additionally, railways lower transportation costs for workers, making commuting easier and enhancing labor mobility. As railways connect previously isolated areas, laborers gain access to more employment opportunities, reducing wage disparities across regions. Thus, railway development influences wage levels and shapes labor movement patterns, contributing to more balanced labor markets and standardized working conditions. Presented below is a proposed panel estimator designed to capture the influence of the total railway length within a province on labor dynamics within a specific sector:

$$W_{it} = \alpha L_{it} + \sum_{i=1}^N \beta_i Z_i + \sum_{t=t_0}^T \gamma_t Z_t + \epsilon_{it} \quad (10)$$

Here,  $W_{it}$  represents the labor count within a given industry or sector for province  $i$  during time  $t$ . The coefficient  $\alpha$  holds significance as it quantifies the influence of railway development on labor dynamics.  $L_{it}$  stands for the total railway length in province  $i$  and time  $t$ , encapsulating the railway infrastructure's extent. Moreover,  $Z_i$  and  $Z_t$  serve as year and province dummy variables, respectively, functioning to capture fixed effects associated with years and provinces. These elements collectively contribute to unraveling the intricate relationship between railway expansion and labor trends within specific sectors.

## 5 Results

### 5.1 Market Integration Dynamics in the Presence of Railway

The investigation into market integration dynamics amid the emergence of railway infrastructure unfolds a nuanced narrative within the historical context of 19th-century Prussia. This section delves into the core findings that illuminate the intricate interplay between railway development and the integration of markets across different cities. By applying innovative analytical techniques and drawing from a comprehensive datasets, this study uncovers the multifaceted effects of railway connectivity on the pricing of commodities and the broader economic landscape.

The Table 1 presents the outcomes derived from panel data fixed effect estimators, offering insights into the effects of log railway distances on log relative prices. The prices analyzed in this section are standardized to prices in the year 1913, and they reflect the log relative prices of various commodities. The data stem from 14 cities situated in Prussia. Notably, the time-based distances, calculated using Dijkstra's shortest path algorithm, are a product of the railway's influence, considering train speed at 60 km/hour and foot speed at 5 km/hour for precise time measurements. Consequently, the observed distances demonstrate a reduction over time, as railway expansion and improved stations

lead to shorter travel times. The analysis also accounts for year and city fixed effects to mitigate potential confounding factors. The results underscore the intricate interplay between temporal evolution, railway advancement, and their impact on market dynamics, effectively shaping the log relative prices of commodities.

Table 1: Effects of log railway distances on log relative prices

	<i>Dependent variable: <math>\ln(P_{ijt}/P_{ijt})</math></i>			
	Rye	Wheat	Barley	Oats
Constant	0.0817*** (0.0095)	-0.0198 (0.0437)	-0.2257*** (0.0758)	0.0809*** (0.0175)
$\ln(D)$	0.0073* (0.0040)	0.0545*** (0.0186)	0.1911*** (0.0411)	0.0129* (0.0077)
City FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	1842	1698	336	1070
$R^2$	0.3925	0.3315	0.5969	0.3516
Adjusted $R^2$	0.3731	0.3083	0.5194	0.3157
F Statistic	20.2183***	14.2674***	7.7050***	9.8073***

*Note:*

\*p<0.1; \*\*p<0.05; \*\*\*p<0.01

The results of the analysis reveal compelling insights into the relationship between log railway distances and log relative prices for different commodities within 19th-century Prussia. The coefficient for the natural logarithm of railway distance ( $\ln(D)$ ) holds key information about the impact of transportation infrastructure on market dynamics.

For Rye, the coefficient of 0.0073 indicates a positive association with log relative prices. This suggests that an increase in log railway distance corresponds to higher log relative prices for rye. This could be attributed to the higher transportation costs associated with areas that are more distant from markets. Similarly, the coefficient for Wheat stands at 0.0545, highlighting a positive relationship. This implies that as log railway distance increases, the log relative price of wheat tends to rise. This is consistent with the notion that regions situated farther from markets experience elevated wheat prices due to transportation expenses.

The coefficient for Barley, at 0.1911, further reinforces the positive link between log railway distance and log relative prices. As log railway distance increases, the log relative price of barley is observed to increase. This underscores the influence of transportation costs on barley prices in more distant areas. The coefficient for Oats is 0.0129, indicating a positive association with log railway distance. This suggests that higher log railway distances are associated with elevated log relative prices for oats. This could be a consequence of increased transportation costs affecting regions farther from markets. The significance levels of these coefficients add further depth to the analysis. The observed relationships are supported by their significance, signifying meaningful connections between log railway distances and log relative prices for each commodity.

Regarding the Table 2, the second phase involves examining market integration and railway development through the lens of Engel's 1995 model. This step entails assessing the impact of log railway distances on the variance of log relative prices, as per Engel's model. The analysis involves averaging the results over a span of 10 years to comprehensively understand the effects of transportation infrastructure on price variance.

Table 2: Effects of log railway distances on variance of log relative prices (Engel's 1995 model) average over the period of 10 years

	<i>Dependent variable: <math>\text{Var}(\ln(P_{iT}/P_{jT}))</math></i>			
	Rye	Wheat	Barley	Oats
Constant	0.009*** (0.002)	-0.334 (0.221)	0.018 (0.011)	0.005 (0.003)
$\ln(\bar{D})$	-0.002** (0.001)	0.231** (0.105)	-0.006 (0.006)	0.001 (0.002)
City FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	186	174	36	110
$R^2$	0.606	0.439	0.745	0.395
Adjusted $R^2$	0.581	0.401	0.670	0.334
F Statistic	24.344***	11.524***	9.878***	6.454***

Note:

\*p<0.1; \*\*p<0.05; \*\*\*p<0.01

In Table 2, for Rye, the coefficient of  $\ln(\bar{D})$  (-0.002) reveals an inverse relationship between the log of average railway distance and the variance of log of relative prices. In simpler terms, as the average railway distance between cities increases, the variance in Rye prices decreases. This suggests that improved rail connectivity between cities led to a more synchronized and integrated market for Rye, reducing price disparities across locations.

In the case of Wheat, the coefficient (0.231) indicates a positive and statistically significant relationship. This means that as the average railway distance grows, the variance in Wheat prices also increases. This positive slope suggests that greater distances, possibly due to limited transportation access, contributed to more divergent and volatile Wheat prices across different cities. For Barley and Oats, the coefficients are -0.006 and 0.001, respectively, although they are not statistically significant. While the lack of significance suggests that the observed relationships might be due to chance, the negative coefficient for Barley implies a potential trend of reduced price variance with increased average railway distance, while the positive coefficient for Oats hints at a positive but inconclusive relationship.

To complete the analysis delves into the effects of dummy railway connections on log relative prices using the Callaway & Sant'Anna's DiD Estimator. This technique allows to precisely measure the influence of these connections on price dynamics. The findings, presented in Table 3, unveil the impact of introducing dummy railway connections on the

logarithmic relative prices of commodities. Through this approach, how these connections shape market integration is unveiled and shed light on the intricate relationship between historical transportation development and commodity price convergence.

Table 3: Effects of dummy railway connections on log relative prices (Callaway & Sant'Anna's DiD Estimator)

	<i>Dependent variable: <math>\ln(P_{ijt}/P_{ijt})</math></i>			
	Rye	Wheat	Barley	Oats
ATT	0.1190*** (0.0101)	0.0983*** (0.0098)	0.2008*** (0.0571)	0.1574** (0.0628)

*Note:* \*p<0.1; \*\*p<0.05; \*\*\*p<0.01

The introduction of railway connections between cities, as highlighted by the positive and statistically significant coefficients in Table 3, holds crucial implications for market integration dynamics. The significant increases in the logarithm of relative prices for Rye, Wheat, Barley, and Oats following the establishment of railway connections accentuate the pivotal role of such connections in fostering enhanced market integration. This effect can be attributed to the enhanced accessibility and connectivity facilitated by railways, allowing for smoother and more efficient movement of goods between different regions. For Rye, the coefficient of approximately 0.1190 indicates that the establishment of railway connections between cities led to an average increase of approximately 11.9% in the logarithm of relative prices for Rye. In the case of Wheat, the coefficient of about 0.0983 suggests an average rise of roughly 9.8% in the logarithm of relative prices for Wheat consequent to the implementation of railway connections. Regarding Barley, the coefficient of around 0.2008 denotes an average elevation of approximately 20.1% in the logarithm of relative prices for Barley as a result of introducing railway connections. Lastly, for Oats, the coefficient of approximately 0.1574 implies an average augmentation of around 15.7% in the logarithm of relative prices for Oats upon the establishment of railway connections. The observed increments in relative prices underscore the convergence of prices across geographically dispersed cities. The tangible impact of railway connections on the prices of key commodities, such as Rye, Wheat, Barley, and Oats, highlights how improved transportation infrastructure can significantly influence market interactions. It is plausible to interpret these results as indicative of reduced price disparities among the connected cities, indicating a trend towards a more unified and integrated market.

## 5.2 Varied Effects of Railway on Different Commodities

The impact of railways on various commodities evolved over their development. Initially, railways primarily focused on efficient passenger transportation. However, as railway networks expanded and matured, their influence on commodities changed due to economies of scale. In later stages, railways shifted towards transporting valuable and high-demand materials, as rail transport became advantageous for bulkier and costlier goods. With further development and expanded reach, railways improved accessibility and lowered

transportation costs, making it economically viable to transport even lower-priced commodities. This transformation took railways from passenger-focused services to facilitating the movement of a diverse range of goods.

The outcomes depicted in Table 4 provide insight into the diverse impacts of railway development on different commodities' price variations, with a focus on the commodities that were in higher demand and held greater value. The coefficients linked to the logarithm of total railway length ( $\ln(L)$ ) shed light on the magnitude and direction of these effects. Notably, the analysis underscores that commodities such as Wheat, Rye, Barley, and Oats—commodities that were more sought after and possessed greater value—experienced notable decreases in their coefficient of price variation ( $CoV$ ) due to the expansion of the railway network. Specifically, for these commodities, the coefficients of -0.013, -0.023, -0.018, and -0.009, respectively, signify a reduction in the variability of prices across different provinces of Prussia as railway length increased. These findings emphasize that high-demand, valuable commodities reaped early benefits from improved transportation infrastructure, enjoying greater market integration and price stability across regions. Conversely, railway development had a less pronounced effect on Pork prices, indicating a smaller impact. This underscores the focus on commodities with higher demand and value, as they experienced more significant reductions in price variability and improved regional integration through efficient railways.

Table 4: Effects of log total railway length on CoV of different commodities' prices

	<i>Dependent variable: Coefficient of price variation</i>				
	Wheat	Rye	Barley	Oats	Pork
Constant	0.170*** (0.022)	0.289*** (0.033)	0.263*** (0.036)	0.159*** (0.030)	0.125*** (0.046)
$\ln(L)$	-0.013*** (0.003)	-0.023*** (0.004)	-0.018*** (0.004)	-0.009** (0.004)	-0.005 (0.006)
Observations	38	38	38	38	38
$R^2$	0.372	0.460	0.320	0.142	0.019
Adjusted $R^2$	0.355	0.445	0.301	0.119	-0.008
F Statistic	21.337***	30.712***	16.958***	5.975**	0.700

*Note:*

\*p<0.1; \*\*p<0.05; \*\*\*p<0.01

### 5.3 Role of Railway in Labor Balancing

Market integration and its impact on the labor force is a complex interplay influenced by technology, trade policies, and economic shifts. It transcends geographical boundaries, creating a globalized economy through advancements like railways and highways. This transformation shifts the labor force across primary, secondary, and tertiary sectors, driven by changing demand patterns influenced by technology, policy, and societal changes. Railways have played a crucial role in labor mobility and balancing, contributing significantly to economic and social dynamics. They have facilitated labor movement by

connecting regions and sectors, allowing individuals to seek better opportunities. This has bridged gaps in labor markets, leading to economic growth and skill diversification. Railways have also shaped various labor movements, from rural-to-urban migration during industrialization to supporting seasonal labor shifts. Their impact on labor balancing is closely tied to their broader role in promoting connectivity, reducing spatial disparities, and enhancing labor market efficiency.

The results in Table 5 illuminate the relationship between railway length and labor distribution across sectors (Industry, Agriculture, and Services). The positive coefficient of 151.06 for the Industry sector suggests that each additional kilometer of railway is associated with an increase of about 151 workers in this sector. This indicates that regions with extensive railway networks tend to have more labor participation in industrial activities due to improved accessibility and market connectivity. Conversely, the Agriculture sector exhibits a negative coefficient of -244.74, indicating that each additional kilometer of railway is linked to a decrease of approximately 245 workers in agriculture. This implies a shift of labor away from agriculture, possibly due to mechanization, urbanization, or better opportunities in other sectors. Similarly, the Services sector shows a negative coefficient of -57.54, suggesting that each additional kilometer of railway is associated with a decline of around 58 workers in services, possibly due to urbanization and changing economic landscapes facilitated by railway connectivity.

Table 5: Effects of total railway length on labor force in different sectors

	<i>Dependent variable: Labor number</i>		
	Industry	Agriculture	Services
Constant	52715.77** (24966.32)	422251.44*** (28406.34)	179280.19*** (13538.41)
Railway Length	151.06*** (37.43)	-244.74*** (42.58)	-57.54*** (20.30)
Province FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Observations	52	52	52
R <sup>2</sup>	0.90	0.92	0.95
Adjusted R <sup>2</sup>	0.78	0.82	0.89
F Statistic	7.58***	9.70***	16.81***

*Note:*

\*p<0.1; \*\*p<0.05; \*\*\*p<0.01

To enhance the robustness of the findings, several approaches can be considered. One avenue is to explore the impact of logarithmic transformations on railway length, providing further insight into the relationships. Additionally, normalizing both the dependent and independent variables using the total population of each province can offer an alternative perspective on the connections explored in this study. These methods can help validate and recalibrate the results while maintaining the reliability of the conclusions drawn from the analysis. It's important to note that the conclusions are based on price data spanning

1850 to 1880 from multiple provinces within Prussia.

## 5.4 Robustness Check & Pre-Treatment Trends

Analyzing pre-treatment trends is crucial for comprehending the impact of railway development in 19th-century Prussia. Prussia was a leader in the industrialization movement during this period, focusing on advancements in iron industries and railway network expansion. These two developments were closely connected, with the iron industry requiring better transportation infrastructure, and railways promoting industrial sector growth. This interdependence between industrialization and railways had a significant influence on the region's economic trajectory. Prussia's standardized regulations and proactive communication efforts aimed to enhance market connectivity and reduce price volatility among provinces, anticipating these trends as the railway network expanded. This strategy aimed to create a more stable economic environment.

Table 6 presents a robustness check by excluding year fixed effects in the model analyzing the effects of log railway distances on log relative prices. This comparison ensures the stability of the observed relationships across various years. The consistent patterns in both models affirm that the impact of log railway distances on log relative prices is not merely a result of year-specific factors, bolstering the credibility and reliability of the study's findings.

Table 6: Effects of log railway distances on log relative prices (without year fixed effect)

	<i>Dependent variable: <math>\ln(P_{ijt}/P_{ijt})</math></i>			
	Rye	Wheat	Barley	Oats
Constant	-0.0061 (0.0078)	0.0769* (0.0396)	-0.4816*** (0.0912)	0.0124 (0.0142)
$\ln(D)$	0.0437*** (0.0034)	0.0117 (0.0169)	0.3154*** (0.0498)	0.0430*** (0.0064)
City FE	Yes	Yes	Yes	Yes
Year FE	No	No	No	No
Observations	1842	1698	336	1070
$R^2$	0.2085	0.0167	0.1968	0.1629
Adjusted $R^2$	0.2054	0.0127	0.1871	0.1582
F Statistic	69.0014***	4.1078***	20.2765***	34.4829***

*Note:*

\*p<0.1; \*\*p<0.05; \*\*\*p<0.01

Table 7 conducts a robustness check by excluding year fixed effects from the examination of the effects of log railway distances on the variance of log relative prices (Engel's 1995 model) averaged over a 10-year period. This analysis assesses the stability of results when year-specific factors are removed from the model, reaffirming the importance of railway distances in impacting price variance. This rigorous approach enhances the credibility

of observed associations and emphasizes the role of railway connectivity in influencing relative price dispersion across commodities.

Table 7: Effects of log railway distances on variance of log relative prices (Engel's 1995 model) average over the period of 10 years (no fixed effects)

	<i>Dependent variable: <math>Var(\ln(P_{iT}/P_{jT}))</math></i>			
	Rye	Wheat	Barley	Oats
Constant	-0.008*** (0.002)	0.650** (0.308)	0.001 (0.021)	-0.004 (0.004)
$\ln(\bar{D})$	0.005*** (0.001)	-0.108 (0.080)	0.004 (0.005)	0.004*** (0.001)
City FE	No	No	No	No
Year FE	No	No	No	No
Observations	186	174	36	110
$R^2$	0.255	0.010	0.019	0.136
Adjusted $R^2$	0.251	0.005	-0.010	0.128
F Statistic	63.052***	1.793	0.656	16.945***

*Note:*

\*p<0.1; \*\*p<0.05; \*\*\*p<0.01

## 6 Interpretation

### 6.1 Market Integration Mechanism & Significance of Railway

Market integration embodies the intricate process by which diverse markets become interconnected, transcending geographical and institutional boundaries to function as a unified whole. This amalgamation of markets occurs on various scales, ranging from local to global, and is closely aligned with the broader concept of globalization, marked by the heightened interdependence of economies and societies worldwide. Crucial components facilitating market integration include advancements in transportation, communication, and trade policies. Technological progress, such as the expansion of railways, highways, maritime trade routes, and modern digital networks, has significantly diminished the cost of moving both goods and information across vast distances. Simultaneously, trade agreements and policies aimed at reducing barriers, such as tariffs and quotas, play a pivotal role in smoothing the integration process. The interplay of these multifaceted elements engenders a dynamic environment where market integration flourishes, fostering increased cross-border exchanges, resource allocation, and economic cooperation.

The significance of railways is profound and multifaceted. Railways have played a pivotal role in catalyzing economic development, transforming societies, and shaping global connectivity. Their establishment marked a turning point in transportation, allowing for the efficient movement of goods and people over extensive distances. In the context of the 19th century, railways were integral to the industrialization process, facilitating the

expansion of industries and the movement of raw materials and finished products. This synergy between railways and industrialization fostered economic growth, as regions endowed with natural resources could now transport them to manufacturing centers with ease. Moreover, railways spurred urbanization by enabling the concentration of industries in urban areas and facilitating labor movement from rural to urban spaces. Beyond economic implications, railways acted as conduits for cultural exchange and social interaction, bridging disparate communities and enhancing the flow of ideas. The advent of railways thus stands as a testament to their enduring significance in shaping the course of history, enhancing trade networks, and propelling societies towards progress and interconnectedness.

## 6.2 Additional Determinants

Indeed, the dynamics of market integration are influenced by a myriad of additional determinants that extend beyond economic factors. These multifaceted determinants encompass a range of elements such as political decisions, historical events, and demographic shifts. Political considerations, including regulations, trade policies, and geopolitical relations, can either facilitate or hinder cross-border trade and cooperation. The impacts of war shocks and conflicts can disrupt supply chains, alter trade routes, and reshape regional economic ties. Production policies and technological advancements also play a critical role; innovative manufacturing techniques can create competitive advantages, while production limitations can affect the availability and affordability of goods. Changes in borders, influenced by geopolitical factors or negotiations, can reshape trade patterns and market interactions. Financial policies, including exchange rates and monetary regulations, can impact the cost of trade and investment. Demographic changes, such as population growth, urbanization, and immigration, influence labor supply, demand for goods and services, and overall market dynamics. In essence, the interplay of these determinants underscores the complexity of market integration, reflecting the intricate interaction between economic, political, social, and historical forces that collectively shape the global economic landscape.

## 6.3 Comparative Advantage & Labor Relocation

The concept of comparative advantage in production is underscored by the principle that entities, be they regions, nations, or firms, can realize higher efficiency and productivity by concentrating on producing goods or services in which they possess a relatively lower opportunity cost compared to others. This economic concept signifies that even if one entity is less efficient in producing all goods than another, there is still a potential for mutual benefit through specialization and trade. The examination of Prussia's market integration dynamics and the role of railways reveals how comparative advantage played a pivotal role. As railways facilitated enhanced connectivity, the movement of goods between regions was streamlined, enabling areas with distinct comparative advantages to capitalize on their strengths. This dynamic led to the concentration of certain production activities in regions that could produce them more efficiently, ultimately fostering economic growth, diversification, and more efficient resource allocation on a broader scale.

Labor relocation, driven by wage disparities and economic opportunities, was notably influenced by Prussia's expanding railway networks. These railways acted as bridges, connecting job seekers to thriving industries in distant regions. The resulting migration reflects the interplay of infrastructure, market integration, and human capital mobility, shaping economic prospects across sectors and locales.

## 6.4 Communication Effects VS. Community Effects

Communication Effects revolve around the dissemination of information and trade activities among various economic entities. Enhancements in communication infrastructure, such as railways, telegraph lines, and digital networks, have played a crucial role in reducing information asymmetry and fostering trade relationships across different regions. This improved connectivity facilitates the exchange of goods, services, and knowledge, contributing significantly to the overall process of market integration.

Conversely, Community Effects manifest through shared policies, strategies, and collaborative initiatives binding economic entities within specific regions or sectors. This sense of community fosters the development of common standards, regulations, and cooperative agreements. By aligning policies and forging partnerships, economic agents within a community create an environment conducive to coordinated actions. This synergy enhances their ability to collectively address challenges, capitalize on comparative advantages, and navigate complex market dynamics more effectively.

## 7 Conclusion

Navigating the intricate landscape of 19th-century Prussia, this study uncovers the multifaceted impacts of railway development on various facets of the economy, industry, and demographics. By examining the nexus between railway expansion and crucial economic indicators like trade, inland transportation, and labor mobility, the research unveils the transformative influence of enhanced connectivity. Central to the study's focus is the profound impact of industrialization and railway advancement on market integration, seen through the lens of commodity prices.

Through an in-depth analysis of historical and economic data, the study sheds light on how railway development intricately shaped the coherence of Prussian markets during the 19th century. This investigation reveals the dynamic interplay between railway infrastructure, market dynamics, and societal progress, offering valuable insights into the ways technological advancements steered historical economic trajectories. These findings collectively illuminate the pivotal role of railways in bridging geographical gaps, fostering market unity, and catalyzing economic development in a rapidly evolving landscape. As we reflect upon these discoveries, we gain a deeper appreciation for how the intricate threads of railway development intricately wove the fabric of Prussia's economic and social tapestry during this transformative era.

As avenues for future research, several intriguing directions emerge from the current study's insights. Exploring the speed of convergence in price among integrated markets could provide deeper understanding into the temporal dynamics of market integration. Investigating the impacts of various shocks on price differences across different cities could

unveil how resilience varies across regions and sectors. Moreover, delving into the roles and policies that influence price disparities offers an opportunity to comprehend the broader economic landscape in relation to market integration.

Extending the analysis by incorporating factors such as population and religious demographics could offer fresh perspectives on the intricate relationship between societal characteristics and market integration. Examining the influence of railway development on the power dynamics of monopolistic sectors post-industrialization could provide insights into the evolution of economic concentration. Additionally, exploring the ramifications of improved railway connectivity on port cities located near seas could illuminate the trade-offs between railway networks and maritime routes.

## A Appendix 1

### Dijkstra's Shortest Path Algorithm

This appendix focuses on using Dijkstra's algorithm to find optimal railway routes based on real railway data and station details. Dijkstra's algorithm, rooted in graph theory, proves valuable for optimizing navigation within complex railway networks, accommodating the intricacies of modern transportation systems. It offers an adaptable solution for efficiently navigating rail-connected urban centers.



Figure 13: Map of Prussia

This comprehensive railway data structure, resembling a city-node and railway-edge graph, empowers the application of Dijkstra's algorithm for route optimization. Within this framework, cities serve as nodes, connected by railways representing edges with associated attributes like distances and station information. These components enable the algorithm to calculate the most efficient paths between origin and destination pairs, making it a valuable tool for optimizing railway travel routes in complex urban networks.

The dataset incorporates Geographic Information System (GIS) data, featuring geographic coordinates for railway stations and lines across Prussia. A noteworthy aspect is the inclusion of each line's starting point, introducing a temporal dimension to the dataset. It reflects varying mapping precision, accommodating both accurately traced railway paths and straight-line approximations between station nodes for computational efficiency. While primary stations are meticulously documented, minor stations continue to be added, reflecting the evolving nature of railway infrastructure.

## Algorithm Description:

Dijkstra's algorithm is well-suited for finding shortest paths within a weighted graph, applicable to our railway system representation (graph  $G = (V, E)$ ). In this context,  $V$  represents cities or stops, and  $E$  denotes railways connecting these nodes, each with weights reflecting real-world attributes like distances or travel times. Specifically,  $L(V_i, V_j)$  denotes the weight between vertices  $V_i$  and  $V_j$ . Dijkstra's algorithm determines minimal cumulative path lengths from a starting node to all others, providing optimal routes and associated distances. To adapt Dijkstra's algorithm for railway data, we apply a greedy approach, systematically updating distances from the start node to find the shortest paths in the graph.

To tailor Dijkstra's algorithm for railway data, we modify edge weights to represent rail-specific factors like distance, time, or cost, enabling the algorithm to find optimal routes considering railway characteristics and constraints. In mathematical parlance, this adaptation can be succinctly summarized. Let  $G = (V, E)$  be the weighted graph representing the railway network, where  $V$  denotes cities or stops, and  $E$  signifies railways. The weight of edge  $e = (V_i, V_j)$  is denoted as  $w(e)$ , encapsulating rail-specific attributes. Dijkstra's algorithm proceeds as follows:

1. Initialize all vertex distances as infinity, except the start vertex, for which the distance is set to 0.
2. Select the unvisited vertex  $u$  with the smallest tentative distance.
3. For each neighbor,  $v$  of  $u$ , calculate the tentative distance through  $u$ , denoted as  $distance_{through_u}$ . If  $distance_{through_u}$  is smaller than the currently assigned distance to  $v$ , update  $v$ 's distance with  $distance_{through_u}$ .
4. Mark  $u$  as visited and repeat steps 2-3 until all vertices are visited.
5. The distances attained represent the shortest paths from the start node to all other nodes.

Adapting Dijkstra's algorithm with railway-specific attributes revolutionizes transportation analysis, replacing simplistic city-to-city distances with accurate time-based railway distances, significantly enhancing precision and potentially transforming our understanding of transportation dynamics and economic impacts within the railway network.

## B Appendix 2

### Multiple periods and variation in treatment timing

The framework presented here extends the Difference-in-Differences (DiD) methodology to scenarios characterized by more than two time periods and varying treatment timings. This adaptation becomes relevant when treatment effects exhibit heterogeneity across time or units, rendering the conventional Two-way Fixed-effects approach inadequate. The notational conventions adhere to those established by Callaway and Sant'Ann (2021), allowing for consistent representation of the underlying concepts. In instances where the number of time periods exceeds two and treatment timing varies across units, this extension serves as a valuable tool for more nuanced analysis, enabling researchers to explore intricate temporal patterns and treatment effects within complex settings.

- $Y_{it}(0)$  is the potential outcome for unit  $i$
- $Y_{it}(g)$  is the potential outcome for unit  $i$  in time period  $t$  if it's treated in period  $g$
- $Y_{it}$  is the observed outcome for unit  $i$  in time period  $t$

For never-treated group:

$$Y_{it} = Y_{it}(0)$$

For other groups:

$$Y_{it} = 1\{G_i > t\} Y_{it}(0) + 1\{G_i \leq t\} Y_{it}(G_i)$$

- $G_i$  is the time period when  $i$  is treated
- $C_i$  is a dummy when  $i$  belongs to the never-treated group
- $D_{it}$  is a dummy for whether  $i$  is treated in period  $t$

The analysis of treatment effects in settings with more than two time periods and varying treatment timings relies on several key assumptions. These assumptions provide the foundation for conducting accurate causal inference through the Difference-in-Differences (DiD) framework. Here are the relevant assumptions:

- **Staggered Treatment Adoption:** Once treated, a unit's treatment cannot be undone or reversed, reflecting the lasting impact of interventions.
- **Parallel Trends (Conditional on Covariates):** In the absence of treatment, potential outcome trajectories for treated and untreated groups would have followed similar paths over time, accounting for covariates.
- **Similarity of Control and Treated Groups (Never-Treated Units):** Before treatment, the average change in potential outcomes for the never-treated group equals the treated group that becomes untreated, ensuring comparable starting points.

- **Similarity of Control and Treated Groups (Not-Yet Treated Units):** The average change in potential outcomes for not-yet treated units mirrors the treated group that will receive treatment in the future, aligning starting conditions.
- **Utilization of Not-Yet Treated Units for Comparison:** Not-yet treated units serve as comparison groups for estimating treatment effects in the future treated group, enhancing accuracy.
- **Random Sampling:** Data collection involves random sampling to ensure that findings are representative of the broader population.
- **Group-Time Average Treatment Effect (ATE):** This measure estimates treatment effects over multiple time periods, akin to the standard ATE but extended to accommodate various time points and treatment timings.
- **Identification Using Parallel Trends Assumption:**
  - Based on Never-Treated Units: Compares treated units with a control group assuming similar trends in the absence of treatment.
  - Based on Not-Yet-Treated Units: Compares treated units' potential outcomes with those not yet treated, accounting for trend differences.
  - Conditional on Covariates: Enhances identification by adjusting for covariates, providing more accurate treatment effect estimates over time.

Possible parameters of interest are:

1. Average treatment effect per group:

$$\theta_S(g) = \frac{1}{\tau - g + 1} \sum_{t=2}^{\tau} 1\{\leq t\} ATT(g, t)$$

2. Average treatment effect across groups (that were treated) (similar to average treatment effect on the treated in the canonical case):

$$\theta_S^O := \sum_{g=2}^{\tau} \theta_S(g) P(G = g)$$

3. Average treatment effect in period  $t$  for all groups that have treated by period  $t$ ):

$$\theta_C(t) = \sum_{g=2}^{\tau} 1\{g \leq t\} ATT(g, t) P(G = g \mid g \leq t)$$

## C Appendix 3

The table below presents data statistics utilized in the research's tables and figures. The corresponding metric for each data is specified in the respective figure.

Table 8: Data statistics

Data	Figure	Obs	Year Range	Min	Max	Mean
Prussia Population	2	71	1840-1913	32621	64568	44624
Railway Length	2	8	1840-1913	133	47771	18324
Iron Consumption	4	21	1851-1871	318513	1808805	881992
Machine Factory	4	6	1846-1875	417	2530	1204
Import	5	38	1834-1871	318	2875	976
Export	5	38	1834-1871	423	2564	926
Railway Share	6	15	1840-1910	0.4	81.8	61.3
Passenger Traffic	7	34	1880-1913	6480	41205	18570
Freight Traffic	7	34	1880-1913	13041	61744	31392
Passenger Growth	8	8	1840-1913	1.3	31	9.9
Freight Growth	8	8	1840-1913	4.2	65.5	16.9
Passenger Price	9	40	1840-1879	3.2	4.9	4.2
Freight Price	9	40	1840-1879	4.4	18	8.2
Passenger Revenue	12	40	1840-1879	0.88	141.3	54.9
Freight Revenue	12	40	1840-1879	0.09	383.5	127.4
Investment	12	40	1840-1879	10.2	650	122.2

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I hereby certify that I have completed this work independently and without using any tools other than those specified, have not yet submitted it to another examination authority, and have not yet published it.

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